Lifecycle Cost Analysis for Operations and Maintenance Planning of Railway Bridge Transition

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LCA for Railway Bridge Transition

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Abstract— **The understanding of the whole-life costs of each component in engineering project could help track or asset manager to decide the optimal maintenance planning for the project. The understanding can help stakeholders to make better choice of track maintenance plans tailored for their local condition. At railway bridge transition (or the interface between plan track and bridge), a track stiffness difference occurs and causes an intense impact force to the rail and vehicle. Many track solutions have been developed over a number of years. However, ballast bonding and embankment treatment are two of the most widely used mitigation methods to reduce the consequences due to their availability, resilience, constructability and maintainability. Currently, the whole-life costs of these methods are not fully understood; therefore, this paper is the first to examine the lifecycle cost and benefits of each mitigation method. Based on the parametric studies, we found that the whole lifecycle costs of maintenance are considerably affected by the economic conditions where discount rate and consumer price index incremental rate are different. The recommendation translates novel insights considering systems thinking approach and socio-technical complexity into practice, and will benefit the railway industry significantly over the long term, enhancing economic sustainability.**

Keywords—ballast bonding, bridge transition, embankment treatment, lifecycle cost, economic sustainability.

I. Introduction

Nowadays, railway networks, e.g. light rail, metro, urban and suburban railways and freights, are rapidly expanding worldwide. In order to cope with diverse geography, i.e., mountains, terrains and rivers, and provide an economical route for railway line, special infrastructure such as bridges and tunnels are designed. The efficiency and sustainability of railway system can be optimal by the design and usage of infrastructure that yields high benefits with low economic and environmental cost. However, various problems can be caused by inadequate design and construction of the interface between different infrastructure types along the railway line [1-5]. These problems could also be aggravated by inappropriate maintenance methods and routine frequency [6-8].

There are two main types of track systems, namely, ballasted track and slab track, which are widely used in present days. On a single railway route, both ballasted track and slab track can be used in the same line to tackle geographical challenges such as slopes and terrains, rivers and oceanic channels, etc. The transition zone, where ballasted track and slab track are joined, has a differential settlement (i.e. a track can displace 2mm to 5mm whilst a bridge generally displaces less than 1mm), which causes a serious problem in operations and maintenance. Trains travelling over the differential settlement often suffer by inducing poor passenger ride comfort and excessive noise radiation [9-11]. The transition zone between the tracks on embankment substructure and the tracks on the bridge are commonly referred to as 'bridge transition' in practice. At the bridge transition, the different in track stiffness can cause an intense vibration and dynamic impact force to the rail and vehicle [12-17]. Therefore, the bridge transition must be designed, operated and maintained to reduce the effects to avoid any detrimental damage to both track and vehicles. One of the methods, which are widely used to mitigate the problems, is ballast bonding [18-19]. It provides a gradually increase stiffness of the track on embankment substructure to match the stiffness of the track on the bridge. Embankment treatment is another commonly used method. It mitigates the problem by the same principal as ballast bonding. However, it gradually changes the track stiffness of the embankment and foundation to match the bridge structure by using different type of materials with different property in different zone at the transition [12]. Fig. 1 shows a typical railway track and the interface of track stiffness.

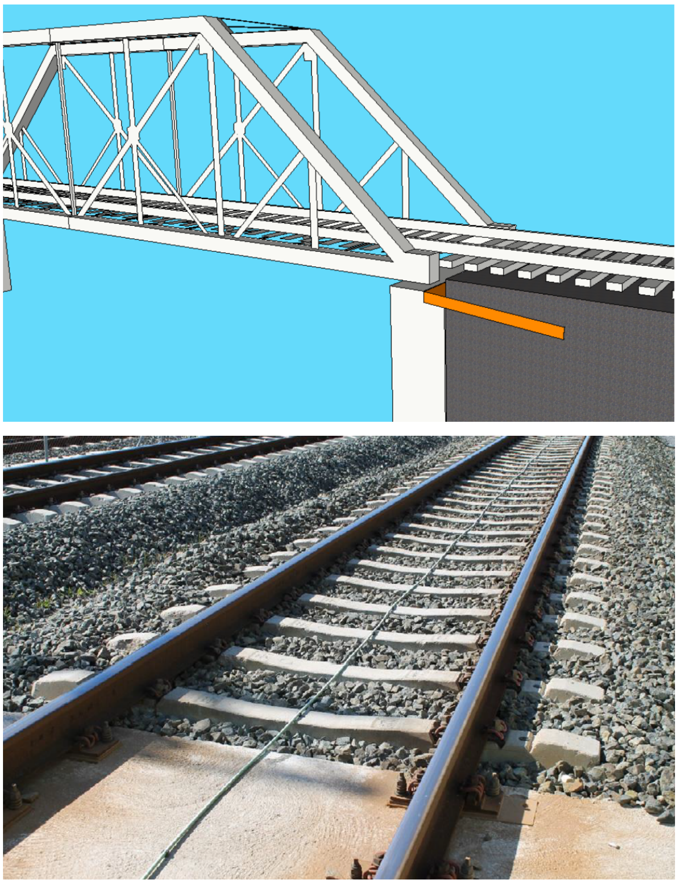

Fig. 1. Interfaces between railway bridges and a plain track [1, 16].

In reality, there are two main transition zone design options [18]:

• Option 1: equalize the stiffnesses and rail deflections of the ballasted and slab tracks by moderating the resilience of the rail on the slab track or the ballasted track over the bridge. A sensible solution is to reduce the stiffnesses of both the slab track and the track over bridge to match the ballasted track stiffness by inserting softer elastic materials.

• Option 2: Provide a gradual stiffness increase (or stiffness ramp) in the ballasted track to match the stiffness of the slab track or the ballasted track over the bridge.

Since low track stiffness can cause track settlement while the exceed of track stiffness can increase the dynamic load and track deterioration, the track stiffness should be controlled at optimum level. The vertical track stiffness as suggested by the UK Rail Safety and Standards Board is 80-130 kN/mm [20].

In this study, the lifecycle cost analysis on the bridge transition maintenance over the course of 50 years will be considered since most railway tracks are designed for services of around this time [21]. The study will be done on a 100 meters double tracks railway bridge. The sensitivity of the whole life cost and the percentage of cost saving, compared to the one where no mitigation method is applied, will be determined. The parametric studies varying the discount rate and Consumer Price Index (CPI) rate will be highlighted as these parameters reflect real-term economic conditions. The study aims to provide a best-practice guideline on the mitigation method in order to facilitate decision making process in different economic conditions, which is one of the grand challenges in transportation and transit systems [22].

II. LITERATURE REVIEW

Railway infrastructure can be made up from various materials, e.g., wood, steel and concrete. Due to the difference of material's mechanical properties, the elasticities are different. Different elasticity has a negative impact on track stiffness. As a consequence, it may require frequent unplanned maintenance at the transition zone [23-24].

There are number of methodologies can be used to mitigate and monitor the stiffness differential at the transition zone [25] One of the most common methods in practice is ballast bonding. Ballast bonding or ballast glue improves the railway tracks' dynamic behavior by changing the behavior and characteristics of railway ballast. At the transition zone, this method can reduce the ballast settlement and improve the stiffness of ballast track. By applying ballast glue under the sleeper with gradually change of glue area, the stiffness of track will gradually change [18]. By applying ballast bonding technique, the frequency of maintenance can be reduced. It will require tamping once in three years instead of 4 times per year. Therefore, in term of economics, the maintenance cost will be reduced significantly [19].

Another common method used to mitigate the differential stiffness at the transition zone is the embankment treatment. The embankment is the railway substructure and foundation area, which lies underneath the ballast layer. This area is directly affected by vibration and dynamin impact loading conditions, which cause damage to the embankment materials (e.g. plastic deformation, permanent set, slope instability, etc.). To prevent the differential settlement and provide gradually stiffness changing, a special design of embankment stiffness treatment can be done. The embankment treatment is done by gradually changing the types of backfill materials, which has different elasticity characteristics [16]. This method is viable in green field projects (when the railway is newly built on a new earthwork and a new corridor).

III. ENGINEERING ASSUMPTIONS AND COST

To perform the lifecycle cost analysis for the maintenance planning of railway bridge transition on the same baseline, detailed engineering assumptions are very important to benchmark the results. This study will focus on the 100 meters long double-tracks railway bridge under the normal temperature and weather condition. The cost of installation and maintenance will be determined based on time-value financial accounting concept of additional cost and cash flow. The lifecycle cost analysis in this study mainly consider the cost of installation and maintenance. Both method can perform in a similar level; therefore, the indirect cost, e.g., rolling stock damage and maintenance period, will be excluded in this study. The lifespan of the track is assumed to be 50 years; therefore, the lifecycle analysis is schedule into 50 years period. The net present value will be used to consider the total effective cost and benefit at present time.

Without applying any mitigation method, the track will be required for tamping (track geometry and alignment restoration) once every three months to maintain the track stability and restore the right position and coordination of the railway line. The cost of tamping is approximately €4,500 each time.

According to S. Kaewunrune (2014) study, the cost of applying ballast bonding is approximately €15,000. Ballast bonding is not available for maintenance since the bonding will break during the tamping process, which will take place every three years; therefore, the lifespan of ballast bonding is approximately three years. The cost of renewal the ballast bonding after tamping will be €15,000 [18].

From HS2 cost and risk model report (2012), the cost of applying embankment treatment method is approximately €32,000. The lifespan of embankment treatment is 50 years; however, it require a maintenance by stone blowing and compact, reballasting or renewal of materials, which cost approximately €4,500 each year [26].

TABLE I. COST SUMMARY

Mitigation Method	Life Span (year)	Installation Cost (euro)	Maintenance Period (month)	Maintenance Cost (euro)
tamping only	-	-	3	4,500
ballast bonding	3	15,000	36	4,500
embankment treatment	50	32,000	12	4,500

TABLE II. WHOLE LIFE COST PRESENT VALUE (EURO)

Mitigation Method	Discounted Rate				
	2%	*4%*	*6%*	*8%*	*10%*
tamping only	583,111	399,754	293,599	228,341	185,754
ballast bonding	208,748	143,582	105,697	82,357	67,122
embankment treatment	172,201	125,972	99,304	82,950	72,291

All the cost stated above has included the cost of materials, labors and construction. The costs for installation and maintenance for each method are listed in Table I.

IV. WHOLE LIFE COST ANALYSIS

In order to determine the whole life cost of each mitigation methods, the Net Present Value (NPV) needed to be considered. The discounted rate of 2, 4, 6, 8 and 10 percent are applied in the calculations of NPV over the course of 50 years in order to study the sensitivity of discounted rate on the change of whole life cost. Table II shows the NPV of the whole life cost of each mitigation method.

From Table II, it can be seen that both methods, ballast bonding and embankment treatment, can reduce the overall cost of operating and maintaining the bridge transition over 60 percent. The authors calculate the saving percentage of each method at each discount rate and plotted a graph, as shown in Fig. 2, to see the differences and its sensitivity of saving percentage of the two methods.

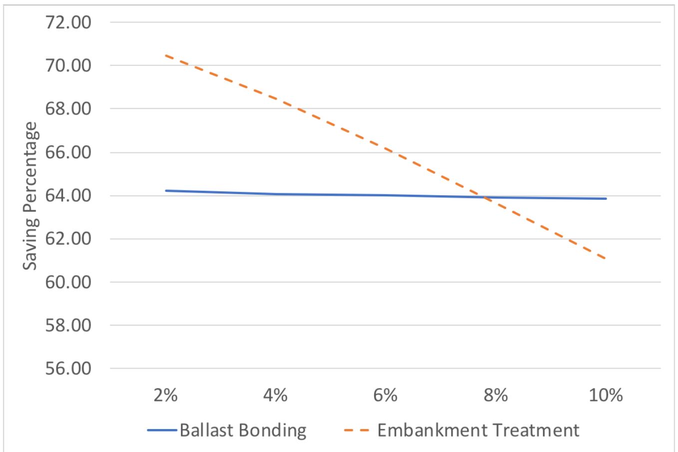

Fig. 2. Saving percentage of each mitigation method

From Fig. 2, it can be seen that, although the discount rate is changing, the saving percentage of ballast bonding method remains almost constant. On the other hand, the saving percentage of embankment treatment reduces significantly as the discount rate increase. It shows that, with a low discount percentage, the embankment treatment method is more suitable since it reduces the maintenance cost approximately 6 percent more than ballast bonding method at the discount rate of 2 percent. With a higher discount percentage, the saving margin between the two becomes smaller and eventually meets at the balance point at about 8 percent discount. At 10 percent discount, the ballast bonding becomes more efficient than the embankment treatment. When making an investment decision, with low discount rate condition (i.e. low growth of economy), the embankment treatment is likely to be a more proper method, and, as the discount rate increases to more than 8 percent, the ballast bonding method will become a more suitable option (for high growth of economy).

V. EFFECT OF RISING IN COMSUMER PRICE INDEX

In the previous section, the NPV are calculated disregarding the rise in CPI (or inflation rate). Due to the rise in CPI, the cost of materials, labors and construction may increase each year. Although the CPI for materials, labors and construction may increase at different rate, the weighted average increasing rates of CPI at 1, 2, 3 and 4 percent on the total cost are considered in this study.

The whole life cost NPVs regarding the increase in the cost due to the rise in CPI have been determined to identify the saving percentage for each mitigation case. Fig. 3-6 shows the saving percentage of each method at each discounted rate regarding the increasing in CPI by 1, 2, 3 and 4 percent respectively.

When consider the effect of the increasing of CPI, the saving percentages are different for each increasing rate. It shows that the saving percentage slightly increase as the CPI increase. It also can be seen that the gap between the two separate wider as the CPI increase. However, it still show the same characteristic at each CPI increase rate where, at lower discount rate, the gap between the two saving percentage is relatively larger than that with higher discount rate. The balance point between the two method change slightly from 8 percent discounted, when there are no increase in CPI, to approximately 9 and 10 percent when the CPI increasing rate are 1 and 2 percent respectively. At the CPI increasing rate longer meet in the interested range. Therefore, at an economic condition where the CPI tend to increase more than 3 percent per year, the embankment treatment should be a more proper method to mitigate the problem.

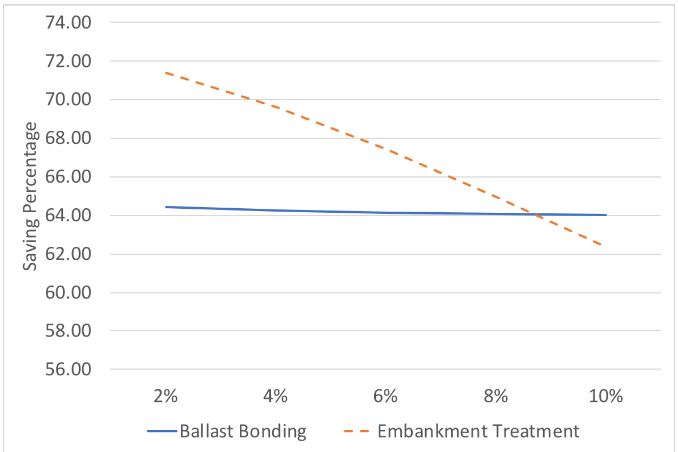

Fig. 3. Saving percentage at CPI increasing rate of 1 percent.

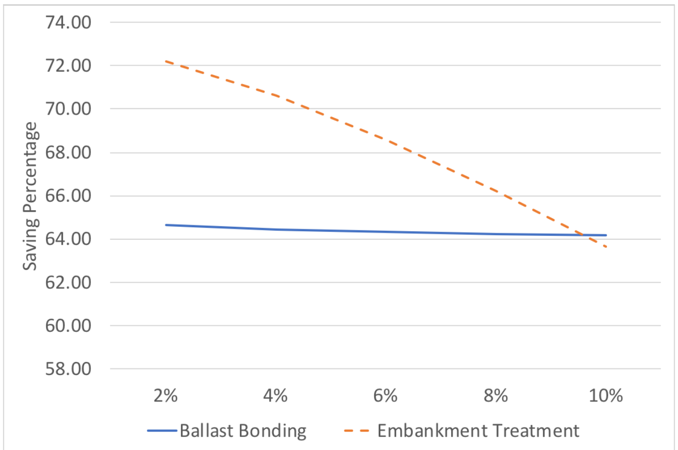

Fig. 4. Saving percentage at CPI increasing rate of 2 percent.

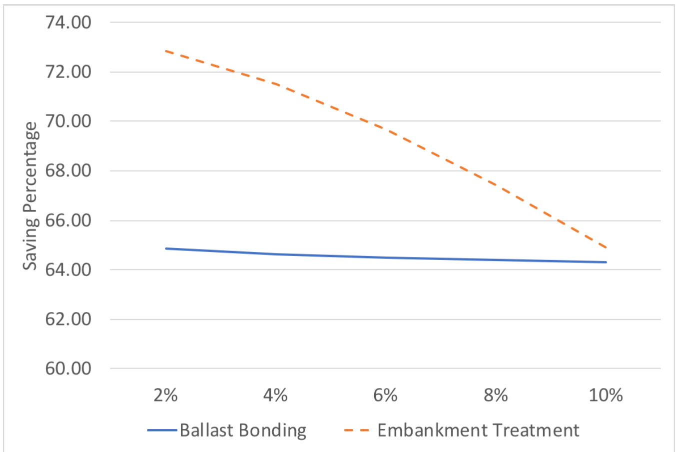

Fig. 5. Saving percentage at CPI increasing rate of 3 percent.

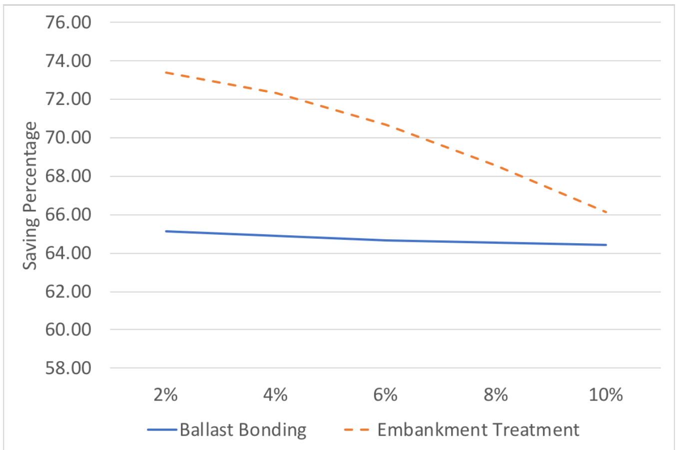

Fig. 6. Saving percentage at CPI increasing rate of 4 percent.

VI. Conclusion

At bridge transitions, the different of stiffness of the track on the bridge and on the plain track can cause detrimental impacts to the infrastructure and the vehicle, which lead to several operational downtime and serious maintenance issues. Ballast bonding and embankment treatment is two of the practical mitigation methods, which are widely used in railway industry.

In this paper, the emphasis is placed on the whole life cost evaluation of those two methods where NPV is considered with regards to the increase in the total cost as a result of the rise in CPI rate. It is founded that, both methods can reduce the maintenance cost over 60 percent while the saving percentage of ballast bonding method stay almost constant, even though the discounted rate has changed. In contrast, the saving percentage of embankment treatment decreases sharply as the discounted rate decrease. At a condition where discounted rate is lower, the embankment treatment can save the cost significantly higher than ballast bonding. In contrast, when the discount rate increases, the saving percentage of the two become close and ballast bonding could be more efficient method at a higher discount rate.

This characteristic remains the same as the CPI increase; however, as CPI rate increase, the gap between the two saving percentage became wider. In the economic condition where the CPI increasing rate is high, the embankment treatment method would yield higher benefits.

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APPENDIX

The NPVs are determined from the incremental cash flow models of each mitigation technique as shown below.

Ballast Bonding		Embankment Treatment	
Year	**Cost**	**Year**	**Cost**
0	15000.00	0	32000.00
1	0.00	1	4500.00
2	0.00	2	4500.00
3	19500.00	3	4500.00
4	0.00	4	4500.00
5	0.00	5	4500.00
6	19500.00	6	4500.00
7	0.00	7	4500.00
8	0.00	8	4500.00
9	19500.00	9	4500.00
10	0.00	10	4500.00
11	0.00	11	4500.00
12	19500.00	12	4500.00
13	0.00	13	4500.00
14	0.00	14	4500.00
15	19500.00	15	4500.00
16	0.00	16	4500.00
17	0.00	17	4500.00
18	19500.00	18	4500.00
19	0.00	19	4500.00
20	0.00	20	4500.00
21	19500.00	21	4500.00
22	0.00	22	4500.00
23	0.00	23	4500.00
24	19500.00	24	4500.00
25	0.00	25	4500.00
26	0.00	26	4500.00
27	19500.00	27	4500.00
28	0.00	28	4500.00
29	0.00	29	4500.00
30	19500.00	30	4500.00
31	0.00	31	4500.00
32	0.00	32	4500.00
33	19500.00	33	4500.00
34	0.00	34	4500.00
35	0.00	35	4500.00
36	19500.00	36	4500.00
37	0.00	37	4500.00
38	0.00	38	4500.00
39	19500.00	39	4500.00
40	0.00	40	4500.00
41	0.00	41	4500.00
42	19500.00	42	4500.00
43	0.00	43	4500.00
44	0.00	44	4500.00
45	19500.00	45	4500.00
46	0.00	46	4500.00
47	0.00	47	4500.00
48	19500.00	48	4500.00
49	0.00	49	4500.00
50	0.00	50	4500.00